Lesson 5

Wet-Film (Packed Tower) Scrubbers

Goal

To familiarize you with the operation, collection efficiency, and major maintenance problems of packed tower scrubbers.

Objectives

At the end of this lesson, you will be able to do the following:

1. Describe the operation of packed tower scrubbers
2. Describe at least three different gas-liquid flow arrangements (designs) for packed tower scrubbers
3. Describe major operating and maintenance problems associated with each packed scrubber design
4. Identify the range of operating values for pressure drop, liquid-to-gas ratio, as well as the collection efficiency of packed tower scrubbers for particles and gases

Introduction

In **packed tower** or **wet-film scrubbers**, liquid is sprayed or poured over packing material contained between support trays. A liquid film coats the packing through which the exhaust gas stream is forced. Pollutants are collected as they pass through the packing, contacting the liquid film. Therefore, both gas and liquid phases provide energy for the gas-liquid contact.

A wet-film scrubber uses packing to provide a large contact area between the gas and liquid phases, turbulent mixing of the phases, and sufficient residence time for the exhaust gas to contact the liquid. These conditions are ideal for gas absorption. Large contact area and good mixing are also good for particle collection; however, once collected, the particles tend to accumulate and plug the packing bed. The exhaust gas is forced to make many changes in direction as it winds through the openings of the packed material. Large particles unable to follow the streamlines, hit the packing and are collected in the liquid. As this liquid drains through the packing bed, the collected particles may accumulate, thus plugging the void spaces in the packed bed. Therefore, wet-film scrubbers are *not* used when particle removal is the only concern. Many other scrubber designs achieve better particle removal for the same power input (operating costs).

Gas Collection

For gas absorption, packed scrubbers are the most commonly used devices. The wet film covering the packing enhances gas absorption several ways by providing:

- A large surface area for gas-liquid contact
- Turbulent contact (good mixing) between the two phases
- Long residence time and repetitive contact

Because of these features, packed towers are capable of achieving high removal efficiencies for many different gaseous pollutants.

Numerous operating variables affect absorption efficiency. Of primary importance is the solubility of the gaseous pollutants. Pollutants that are readily soluble in the scrubbing liquid can be easily removed under a variety of operating conditions. Some other important operating variables are discussed below.

Gas velocity - The rate of exhaust gas from the process determines the scrubber size to be used. The scrubber should be designed so that the gas velocity through it will promote good mixing between the gas and liquid phases. However, the velocity should not be too fast to cause flooding.

Liquid-injection rate - Generally, removal efficiency is increased by an increase in the liquid-injection rate to the vessel. The amount of liquid that can be injected is limited by the dimensions of the scrubber. Increasing liquid-injection rates will also increase the operating costs. The optimum amount of liquid injected is based on the exhaust gas flow rate.

Packing size - Smaller packing sizes offer a larger surface area, thus enhancing absorption. However, smaller packing fits more tightly, which decreases the open area between packing, thus increasing the pressure drop across the packing bed.

Packing height - As packing height increases, total surface area and residence time increases, enhancing absorption. However, more packing necessitates a larger absorption system, which increases capital cost.

Tower Designs

Packed towers are typically designated by the flow arrangement used for gas-liquid contact or by the material used as packing for the bed. The most common flow configuration for packed towers is **countercurrent flow**. Figure 5-1 shows a packed tower with this arrangement. The exhaust stream being treated enters the bottom of the tower and flows upward over the packing material. Liquid is introduced at the top of the packing by sprays or weirs, and it flows downward over the packing material. As the exhaust stream moves up through the packing, it is forced to make many winding changes in direction, resulting in intimate mixing of both the exhaust gas and liquid streams. This countercurrent-flow arrangement results in the highest *theoretically* achievable efficiency. The most dilute gas is contacted with the purest absorbing liquor, providing a maximized concentration difference (driving force) for the entire length of the column. In the other two flow arrangements, the scrubbing liquid could theoretically reach the same concentration as the flue gas (since they are moving in similar directions) and therefore absorption would stop.

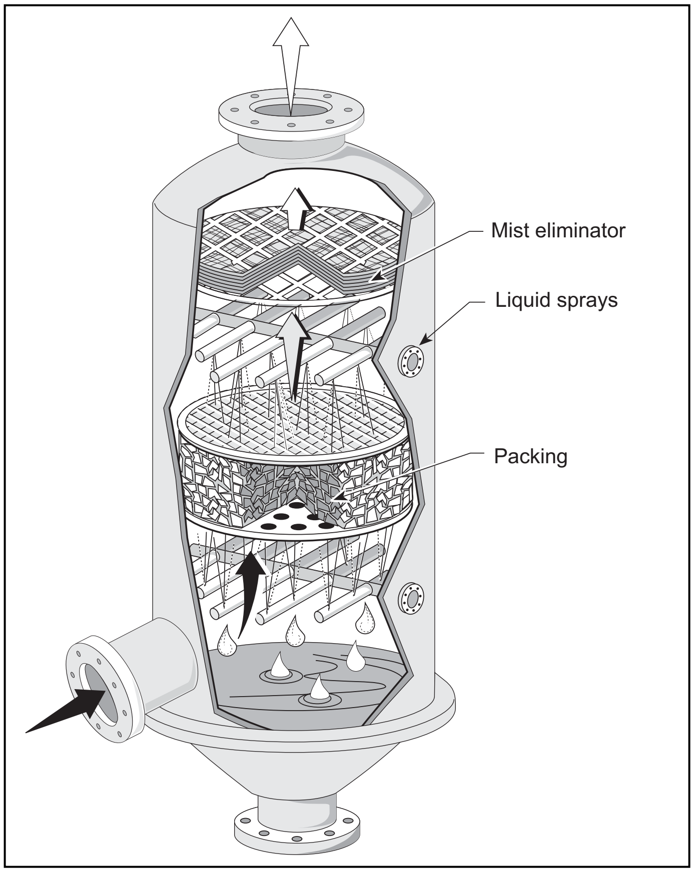


Figure 5-1. Countercurrent-flow packed tower

The countercurrent-flow packed tower does not operate effectively if there are large variations in the liquid or gas flow rates. If either the liquid-injection rate or the gas flow rate through the packing bed is too high, a condition called flooding may occur. **Flooding** is a condition where the liquid is "held" in the pockets, or void spaces, between the packing and does not drain down through the packing. Flooding can be reduced by reducing the gas velocity through the bed or by reducing the liquid-injection rate.

In another flow arrangement used with packed towers, **cocurrent** flow, both the exhaust gas and liquid phases enter at the top of the absorber and move downward over the packing material. This allows the absorber to operate at higher liquid and gas flow rates since flooding is not a problem. The pressure drop is lower than with countercurrent flow since both streams move in the same direction. The major disadvantage is that removal efficiency is very limited due to the decreasing driving force (concentration differential) as the streams travel down through the column. This limits the areas of application for cocurrent absorbers. They are used almost exclusively in situations where limited equipment space is available, since the tower diameter is smaller than that for countercurrent or plate towers for equivalent flow rates. Cocurrent flow is illustrated in Figure 5-2.

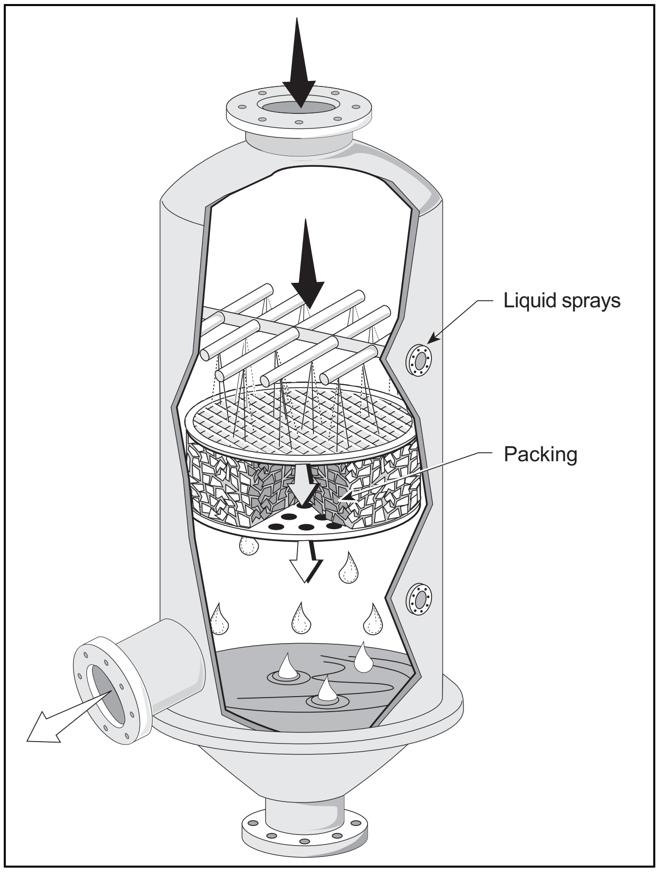


Figure 5-2. Cocurrent-flow packed tower

In packed towers using the **crossflow arrangement**, the exhaust gas stream moves horizontally through the packed bed. The bed is irrigated by the scrubbing liquid flowing down through the packing material. The liquid and exhaust gas flow in directions perpendicular to each other. A typical crossflow packed tower is shown in Figure 5-3. Inlet sprays aimed at the face of the bed may also be included. If included, these sprays scrub both the entering gas and the face of the packed bed. The leading face of the packed bed is slanted in the direction of the oncoming gas stream. This ensures complete wetting of the packing by allowing time for the liquid at the front face of the packing to drop to the bottom before being pushed back by the entering gas.

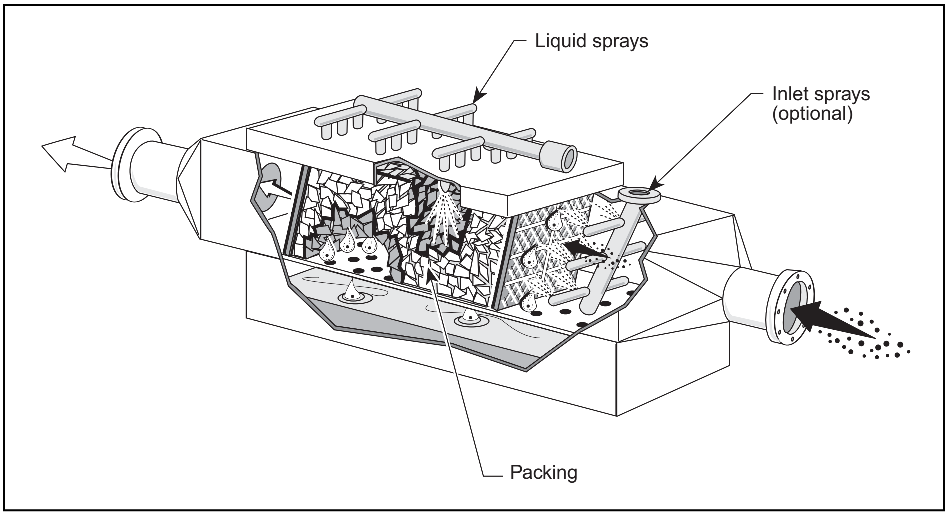


Figure 5-3. Crossflow packed tower

Crossflow absorbers can be designed to be smaller and have a lower pressure drop than any other packed or plate tower for the same application (i.e. removal efficiency and flow rates). In addition, they are better suited than other wet-film scrubbers to handle exhaust streams with high particle concentrations. By adjusting the liquid flow rate, incoming particles can be removed and washed away in the front half of the bed. This also results in a liquid savings by enabling the crossflow packed tower to use less liquid in the rear sprays. This practice is carried one step further by actually constructing the tower into sections as shown in Figure 5-4. The front section can be equipped with water sprays and used for particulate matter removal. In the second section, sprays may contain a reagent in the scrubbing liquor for gas removal. The last section can be left dry to act as an entrainment separator. Crossflow packed towers do require complex design procedures since concentration gradients exist in two directions in the liquid: from top to bottom and from front to rear.

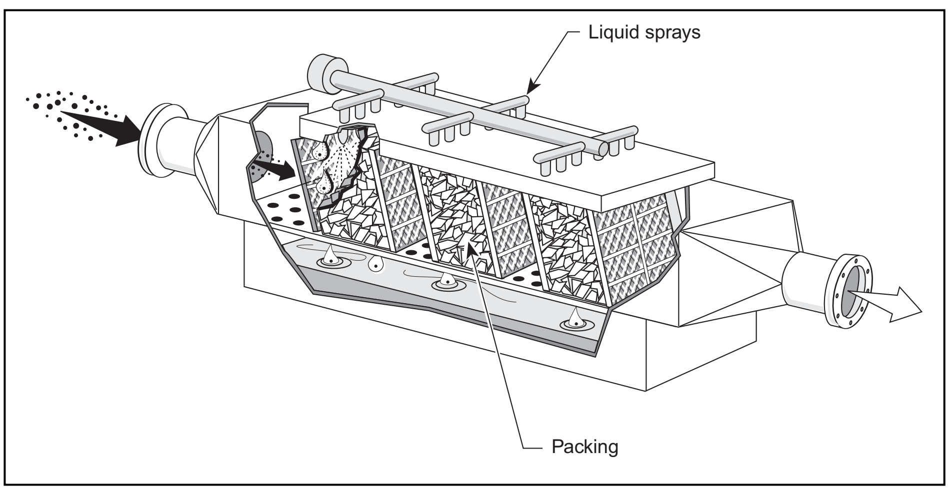


Figure 5-4. Three-bed crossflow packed tower

Another crossflow packed tower is the **fiber-bed scrubber**. The fiber-bed scrubber has packed beds that are made with fibrous material such as fiberglass or plastic (Figure 5-5). Liquid is sprayed onto the fiber beds to provide a wetted surface for pollutant removal and to wash away any collected material.

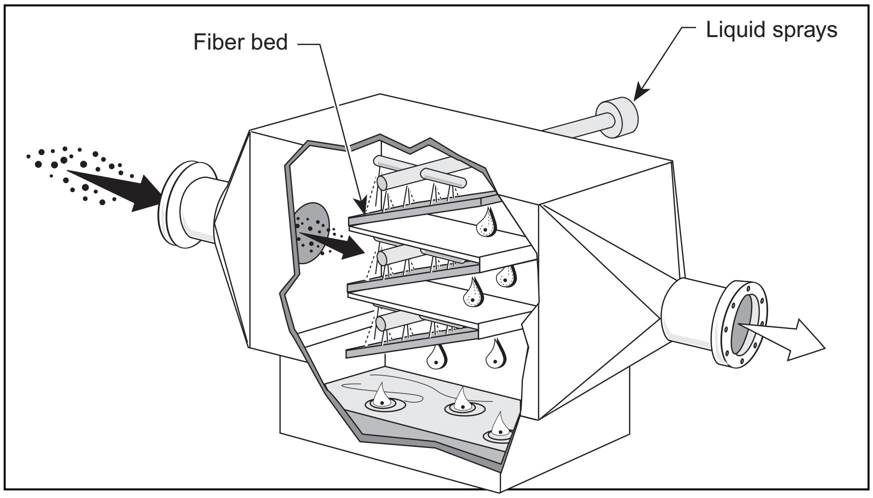


Figure 5-5. Fiber-bed scrubber

Packing Material

Packing material is the heart of the tower. It provides the surface over which the scrubbing liquid flows, presenting a large area for mass transfer to occur. Packing material represents the largest material cost of the packed tower. Pictured in Figure 5-6 are some of the more commonly used packings. These materials were originally made of stoneware, porcelain, or metal, but presently, a large majority are made of high-density thermoplastics (polyethylene and polypropylene). A specific packing is described by its trade name and overall size. For example, a column can be packed with 5-cm (2-in.) Raschig rings or 2.5-cm (1-in.) Tellerette packing. The overall dimensions of packing materials normally range from 0.6 to 10 cm (0.25 to 4 in.).

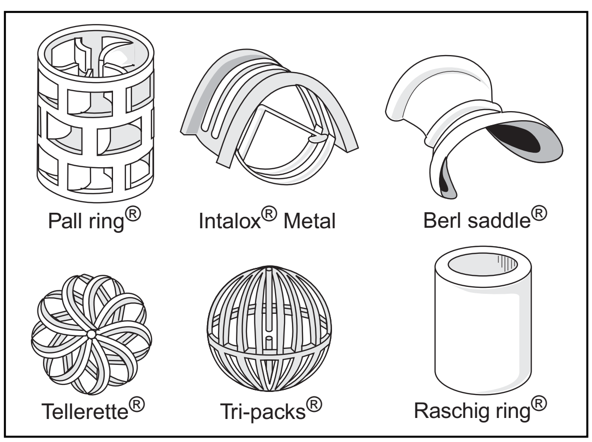


Figure 5-6. Common packing materials

Specific packing selected for an industrial application depends on the nature of the contaminants, geometric mode of contact, size of the absorber, and scrubbing objectives. The following factors provide a general guide for selecting packing materials (MacDonald 1977):

Cost - Generally, plastic packing is less expensive than metal packing, with ceramic packing being the most expensive. Packing costs are expressed in dollars per cubic meter ($/m^3).

Low pressure drop - Pressure drop is a function of the volume of void space in a tower when filled with packing: generally, the larger the packing size for a given bed size, the smaller the pressure drop becomes.

Corrosion resistance - Ceramic or porcelain packings are commonly used in a very corrosive atmosphere.

Large specific area - A large surface area per cubic foot of packing, m^2/m^3 (ft^2/ft^3), is desirable for mass transfer.

Structural strength - Packing must be strong enough to withstand normal loads during installation, service, physical handling, and thermal fluctuations. Ceramic packing may crack under sudden temperature changes.

Weight - Heavier packing may require additional support materials or heavier tower construction. Plastics have a big advantage in this area since they are much lighter than either ceramic or metal packings.

Design flexibility - The efficiency of a scrubber changes as the liquid and gas flow rates vary. Packing material must be able to handle the process changes without substantially affecting removal efficiency.

Arrangement - Packing material may be arranged in an absorber in one of two ways. The packing may be dumped into the column *randomly* or, in certain cases, *systematically stacked*, as bricks are laid atop each other. Randomly packed towers provide a higher surface area, m^2/m^3 (ft^2/ft^3), but also cause a higher pressure drop than stacked packing. In addition to the lower pressure drop, the stacked packing provides better liquid distribution over the entire surface of the packing. However, the large installation costs required to stack the packing material usually make it impractical.

Exhaust Gas Distribution

Uniform distribution of the exhaust gas through the packed beds is very important for efficient pollutant removal. This is accomplished by properly designing the support trays that contain the packing in the bed. The support trays are essentially metal plates, or grids, that support the packing while allowing the exhaust gas to flow evenly into the bed. If the packed tower has multiple packing sections, each support grid acts as a distribution baffle, directing the exhaust gas into the next packing section.

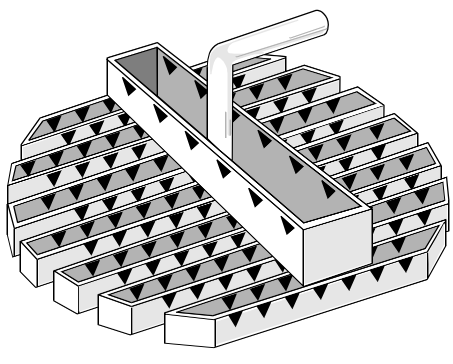
Liquid Distribution

As stated previously, one of the keys to effective packed tower operation is to intimately contact the gas stream with the liquid stream. This contact must be maintained throughout the entire column length. No packing material will adequately distribute liquid poured onto it at only one point. Liquid introduced into the tower in this manner tends to flow down over a relatively small cross section of the tower diameter. Known as **liquid channeling**, the liquid flows in little streams down through the tower without wetting the entire packing area. Liquid should be distributed over the entire cross-sectional top of the packing.

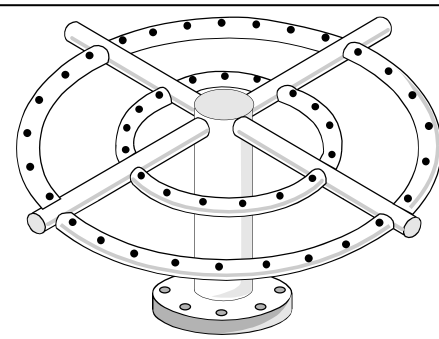
Once the liquid is distributed over the packing, it flows down (by the force of gravity) through the packing, following the path of least resistance. The liquid tends to flow toward the tower wall, where the void spaces are greater than in the center. Once the liquid hits the wall, it flows straight down the tower from that point (liquid channeling). A way must be provided to redirect the liquid from the tower wall back to the center of the column. This is usually done by using **liquid redistributors**, which funnel the liquid back over the entire surface of packing. It is recommended that redistributors be placed at intervals of no more than 3 m (10 ft) or 5 tower diameters, whichever is smaller (Zenz 1972).

Liquid can be distributed over the packing material by one of three devices: weirs, tubes, or spray nozzles. Figure 5-7 shows both the commonly used weir and perforated-tube liquid distributors. In the **weir design**, liquid is introduced into a trough with holes at the top. The liquid fills to the top and "spills" over onto the packing or another trough for redistribution. These weir designs have the advantage of being open and not plugged easily. However when installed they must be level or else the liquid will not be evenly distributed.

The **perforated-tube** provides good liquid distribution patterns, however the holes are subject to plugging if any particles or contaminants are in the liquid. The drilled tube is often buried within the packing bed. This allows the liquid coming out of the holes to be distributed over the packing without being blown against the side walls of the tower. Burying the tube also allows the packing above the tube to act as an entrainment separator for countercurrent flow towers.



(a) Trough and weir liquid distributor



(b) Perforated-tube liquid distributor

Figure 5-7. Two types of liquid distributors

Packed towers, designed with **spray nozzles** to distribute liquid, operate better with a few large nozzles than with many small nozzles. Large nozzles are less susceptible to plugging. Small nozzles that produce a finer spray are not needed in a packed tower because pollutant collection occurs on the wetted packing and not by the liquid droplets. The advantages and disadvantages of each liquid distributor are listed in Table 5-1.

Table 5-1. Liquid distributors for packed towers

Distributor	Advantages	Disadvantages
Weirs	Handle dirty liquids with a high solids content Can use river or unfiltered water Can be easily inspected and maintained if access is available	Most costly to purchase Do not distribute liquid as uniformly as other methods Weirs must be level
Tubes	Uniform liquid distribution Can be buried below packing surface Generally least expensive to purchase	Easily plugged, must use filter Difficult to determine if holes are plugged when tube is buried in the packing
Spray nozzles	Uniform liquid distribution Tower need not be plumb Can be easily inspected and maintained if access is available	Highest pressure drops and operating costs Easily plugged, must use filter

Source: Clark 1975.

Maintenance Problems

A serious problem that can drastically affect the operation of a packed tower is the buildup of solids in the packing. This can occur as a result of a number of situations. If the incoming exhaust gas contains a high concentration of particulate matter, the beds can easily become plugged. Precleaning sprays can reduce this problem by removing particles before the exhaust gas enters the packed bed. Solids buildup can also occur as a result of a chemical reaction between the scrubbing liquid and gaseous pollutant, producing a solid compound. In this case, the packing may occasionally be flushed with a cleaning fluid to remove the solids. For example, potassium permanganate is occasionally used in scrubbing solutions to control odors. The use of potassium permanganate results in a residue buildup on the packing that must periodically be cleaned with an acid backwash. No matter what the cause, plugging presents an expensive maintenance problem. Tower internals are not easily accessible; cleaning requires shutting the system down and then removing, cleaning, and, finally, reinstalling the packing material.

Another critical problem in packed tower operation is maintaining the proper liquid and gas flow rates. If the liquid or gas flow rate increases (one in relation to the other), a point is reached where the rising exhaust gas starts to hold up the descending liquid. The liquid fills the upper portion of the packing until its weight causes it to fall. This condition, known as flooding, results in a high pressure drop, a pulsating airflow in the tower, and greatly reduced pollutant removal efficiencies. Optimum operating flow rates are normally at 60 to 75% of the flooding conditions. Conversely, a gas flow rate that is too low can also cause mixing problems, resulting in gas channeling. **Gas channeling** occurs when the gas does not distribute uniformly through the packing, but moves only through a small portion of the bed (following the path of least resistance). This normally occurs near the walls of the tower, where the void spaces are the greatest. Table 5-2 lists problems that can occur in daily operation of packed towers and some probable causes of these problems.

Table 5-2. Operating problems associated with packed towers

Problem	Possible causes
Static pressure drop increases	Liquid flow rate to liquid distributor has increased and should be checked. Packing in irrigated bed could be partially plugged due to solids deposition, and may require cleaning. Entrainment separator could be partially plugged and may require cleaning. Packing support plate at bottom of packed section could be plugged, causing increased pressure drop, which will require cleaning. Packing could be settling due to corrosion or solids deposition, again requiring cleaning or additional packing. Airflow rate through absorber could have been increased by a change in damper setting, which may need readjustment.
Pressure drop decreases, slowly or rapidly	Liquid flow rate to distributor has decreased and should be adjusted accordingly. Airflow rate to scrubber has decreased due to a change in fan characteristics or due to a change in system damper settings. Partial plugging of spray or liquid distributor, causing channeling through scrubber, could be occurring. Liquid distributor should be inspected to ensure that it is totally operable. Packing support plate could have been damaged and fallen into bottom of the absorber, allowing packing to fall to bottom and produce a lower pressure drop. This should be checked.
Pressure or flow change in recycled liquid causing reduced liquid flow	Plugged strainer or filter in recycle piping, which may require cleaning. Plugged spray nozzles, which may require cleaning. Piping may be becoming partially plugged with solids and need cleaning. Liquid level in sump could have decreased, causing pump cavitation. Pump impeller could have been worn excessively. Valve in either suction or discharge side of pump could have been inadvertently closed.
High liquid flow	Break in the internal distributor piping. Spray nozzle that has been inadvertently "uninstalled." Spray nozzle that may have come loose or eroded away, creating a low pressure drop. Change in throttling valve setting on the discharge side of the pump, allowing larger liquid flow; reset to the proper conditions.

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Table 5-2. *(continued)* Operating problems associated with packed towers

Problem	Possible causes
Excessive liquid carryover	Partially plugged entrainment separator, causing channeling and reentrainment of the collected liquid droplets. Airflow rate to absorber could have increased above the design capability, causing reentrainment. If a packed-type entrainment separator was used, packing may not be level, causing channeling and reentrainment of moisture. If a packed entrainment separator was used, and a sudden surge of air through the absorber occurred, this could have caused the packing to be carried out of absorber or to be blown aside, creating an open area "hole" through separator. Velocity through absorber has decreased to a point that absorption does not effectively take place, and low removal is achieved.
Reading indicating low airflow	Packing in absorber may be plugged, causing a restriction to airflow. Liquid flow rate to absorber could have been increased inadvertently, again causing greater restriction and pressure drop, creating lower gas flow rate. Fan belts have worn or loosened, reducing airflow to equipment. Fan impeller could be partially corroded, reducing fan efficiency. Ductwork to or from absorber could be partially plugged with solids and may need cleaning. Damper in system has been inadvertently closed or setting changed. Break or leak in duct could have occurred due to corrosion.
Increase in airflow	Sudden opening of damper in system. Low liquid flow rate to absorber. Packing has suddenly been damaged and has fallen to bottom of absorber.
Sudden decrease in absorber efficiency	Liquid makeup rate to the absorber has been inadvertently shut off or throttled to a low level, decreasing absorber efficiency. Set point on pH control may have to be adjusted to allow more chemical feed. Problem may exist with chemical metering pump, control valve, or line pluggage. Liquid flow rate to scrubber may be too low for effective removal.

Source: MacDonald 1982.

Summary

Packed towers are mainly used to remove gaseous pollutants. Because of plugging problems, they are not used when particle removal is the only concern, or when a high concentration of particulate matter is in the exhaust gas. Packed towers are capable of very high efficiencies for removing many gaseous pollutants. Packed towers and plate towers are ideal when pollutants are only slightly soluble, or when the gaseous pollutant removal efficiency must be greater than 99%. In a packed tower, the optimum pressure drop through a packing section is 1.7 to 5.0 cm (0.2 to 0.6 in.) of water per foot of installed packing (Clark 1975). The overall pressure drops across packed towers are usually between 5 and 25 cm (2 and 10 in.) of water. Thus, packed towers are generally considered as medium-energy scrubbers.

Packed towers are most suited to applications where a high gas-removal efficiency is required and the exhaust gas is relatively free from particles. These include removing HCl, NH_4, and SO_2 gases from a variety of process streams such as those from fertilizer manufacturing, chemical processing, acid manufacturing, steel making, and metal pickling operations. One important point that should be noted is that packed towers are not effective in removing submicrometer-sized particles, even if the particles are very soluble. Inorganic salts or fumes such as ammonium chloride or aluminum chloride are prime examples. These particles are usually so small that they flow with the exhaust gas through the packing bed and are not absorbed. Table 5-3 lists the general operating characteristics of wet-film scrubbers.

Table 5-3. Operating characteristics of wet-film scrubbers

Pollutant	Pressure drop (Δp)	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure (p_L)	Removal efficiency	Applications
Gases	2-8.5 cm/m of column packing	0.13-2.0 L/m^3	34-100 kPa	Very high, 99^+%, depending on operating conditions	Mainly used for gaseous pollutant removal Metal operations Acid plants Chemical process industries
Particles	(0.25-1 in./ft of column packing)	(1-15 gal/1000 ft^3, depending on type of flow and packing)	(5-15 psig)	2.0 µm diameter	

Plate towers (described in Lesson 3) are used to control emissions from many of the same processes that could use packed towers. Therefore, when gas removal is the only objective, the choice is often between a packed or plate absorber.

The following list gives some factors to consider when comparing plate towers to packed towers:

1. Packed towers are not able to handle particulate matter or other solid materials in the flue gas as well as plate towers.
2. Plate towers are chosen for operations that involve difficult gases to absorb or that must handle large gas volumes. To achieve the same collection efficiency for difficult absorption processes, packed towers must have either deep packed beds or multiple beds. Packed towers can experience liquid channeling problems if the diameter or height of the tower is too large. Redistribution trays must be installed in large-diameter and tall packed towers to avoid channeling.
3. The total weight of a packed tower is more than that of a comparable plate tower.

4. Packed towers are much cheaper to construct than plate towers if corrosive substances are to be handled. Packed towers can be constructed with a fiberglass-reinforced polyester shell which is generally about half the cost of a carbon steel plate tower.

5. Packed towers cannot handle volume and temperature fluctuations as well as plate towers. Expansion or contraction due to temperature changes can crush or melt packing material.

Review Exercise

1. True or False? Packed towers have limited application for particulate removal.

2. Packed towers are frequently used for removing gaseous pollutants because:

   a. The packing provides a large surface area for gas-liquid contact
   b. They have relatively low pressure drops compared to plate towers
   c. The packing provides good mixing of gas and liquid and a long residence time
   d. All of the above

3. Increasing the liquid flow rate in a packed tower will usually ____________________ the gas removal rate.

   a. Increase
   b. Decrease
   c. Have no effect on

4. In a ____________________ packed tower, the gas stream being treated enters the bottom and flows upward through the packing while the liquid is introduced over the top of the packing and flows down through it.

   a. Cocurrent
   b. Crossflow
   c. Countercurrent

5. A ____________________ packed tower cannot handle large variations in liquid or gas flow rates because flooding may occur.

   a. Cocurrent
   b. Countercurrent
   c. Crossflow
   d. Fiber-bed

6. Cocurrent packed towers usually have ____________________ pressure drops than countercurrent packed towers.

   a. Higher
   b. Lower

7. True or False? Crossflow packed towers can handle flue gas containing a high concentration of particulate matter because they use liquid sprays that will remove and wash away particles in the front half of the bed.

8. Packing material is usually made of:

   a. Porcelain
   b. Polyethylene
   c. Polypropylene
   d. All of the above

9. In a packed tower, liquid occasionally flows in little streams straight through the packing without wetting the packing surface. This condition is called:

   a. Flooding
   b. Liquid channeling
   c. Mixing
   d. Plugging

10. In packed tower, liquid is distributed over the packing by using:

    a. Sprays
    b. Sprays and small venturis
    c. Sprays, weirs, and tubes
    d. Chevron-shaped sheets and sprays

11. If the gas flow rate through a packed tower is too low, ____________________ may occur.

    a. Flooding
    b. Mixing
    c. Gas channeling
    d. Plugging

12. True or False? Packed towers are most suitable for industrial processes requiring high gas-removal efficiency, but not having a high concentration of particulate matter in the flue gas.

13. True or False? Packed towers remove particulate matter and other solids more easily and with less maintenance problems than plate towers.

14. In processes having high-temperature flue gas, ____________________ towers are more suitable because their internal components will expand and contract.

    a. Plate
    b. Packed

Review Exercise Answers

1. **True**
   Packed towers have limited application for particulate removal.

2. **d. All of the above**
   Packed towers are frequently used for removing gaseous pollutants for the following reasons:

   - The packing provides a large surface area for gas-liquid contact
   - They have relatively low pressure drops compared to plate towers
   - The packing provides good mixing of gas and liquid and a long residence time

3. **a. Increase**
   Increasing the liquid flow rate in a packed tower will usually increase the gas removal rate because of increasing the potential solubility of the pollutant in the additional liquid.

4. **c. Countercurrent**
   In a countercurrent packed tower, the gas stream being treated enters the bottom and flows upward through the packing while the liquid is introduced over the top of the packing and flows down through it.

5. **b. Countercurrent**
   A countercurrent packed tower cannot handle large variations in liquid or gas flow rates because flooding may occur.

6. **b. Lower**
   Cocurrent packed towers usually have lower pressure drops than countercurrent packed towers. Because the liquid and gas streams move in the same direction in cocurrent packed towers, there is less resistance to flow.

7. **True**
   Crossflow packed towers can handle flue gas containing a high concentration of particulate matter because they use liquid sprays that will remove and wash away particles in the front half of the bed.

8. **d. All of the above**
   Packing material is usually made of porcelain, polyethylene, or polypropylene.

9. **b. Liquid channeling**
   In a packed tower, liquid occasionally flows in little streams straight through the packing without wetting the packing surface. This condition is called liquid channeling.

10. **c. Sprays, weirs, and tubes**
    In packed tower, liquid is distributed over the packing by using sprays, weirs, and tubes.

11. **c. Gas channeling**
    If the gas flow rate through a packed tower is too low, gas channeling may occur.

12. **True**
    Packed towers are most suitable for industrial processes requiring high gas-removal

efficiency, but not having a high concentration of particulate matter in the flue gas. Packed towers are susceptible to plugging.

13. **False**
    Packed towers do NOT remove particulate matter and other solids more easily and with less maintenance problems than plate towers. The tops of plates can usually be accessed through openings, while the middle of the packed bed cannot.

14. **a. Plate**
    In processes having high-temperature flue gas, plate towers are more suitable because their internal components will expand and contract.

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